UNIWERSYTET EKONOMICZNY W KRAKOWIE

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Improving quality management teaching in the era of Industry 4.0

Cracow University of Economics, Poland
Technical University of Košice, Slovakia
Tomas Bata University in Zlín, Czechia

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Analysis of the Current State of Knowledge about Quality 4.0

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Introduction

The global industrial landscape has changed deeply in the last few years and it is a result of technological development and innovations. Industry 4.0 (I4.0) refers to fourth industrial revolution and integration of connected, intelligent technologies that are shaping the way people and industries operate. I4.0 has brought a significant shift in the way organizations approach industrial processes and value creation. It brings benefits for organizations in the form of increased productivity, efficiency, flexibility, and the creation of innovation opportunities. It is considered to be an inevitable driver of performance and competitiveness. Many countries have implemented various national initiatives to support the digital transformation of the industry for ensuring future competitiveness including Visegrad Countries.

I4.0 affects all functional areas of organizations and also the field of quality management. Approaches to quality management have undergone several transformations over the past decades, which were related to technological advancements. The current digital era is challenging the quality profession and its traditional principles, practices, and tools. The merging of new technologies and capabilities with traditional methods and tools of managing quality is culminating in a new Quality 4.0 concept bringing potential benefits like increased efficiency, quality, customer focus and success of innovations. Quality 4.0 concept derived from the I4.0 uses new principles and cutting-edge technologies like the Internet of Things (IoT), Big Data (BD), Could Computing, Artificial Intelligence (AI), Augmented Reality (AR) that requires new knowledge and skills in quality professionals.

The goal of the report is to review the existing literature and internet sources and synthesise current knowledge and information primarily regarding the Quality 4.0 concept as well as related competencies that need to be developed in quality professionals to be able to handle new challenges in the digital era. The report starts with the Industry 4.0 background, definitions and maturity models. It is followed by the overview of Industry 4.0 initiatives on the level of Visegrad countries – Poland, Czech Republic and Slovakia. Subsequently, Quality 4.0 concept is presented and its core principles, features, tools and existing maturity models, as well as existing Quality Management Models (QMM) are discussed in relation to Quality 4.0 concept. The last chapter of the report addresses the competencies (hard and soft) that are crucial for the digital era and also those that should be developed in quality professionals.

Chapter 1. Background and Definition of Industry 4.0

1.1. Industrial Revolution from Industry 1.0 to Industry 4.0

Technical advances change the way humans produce things. Over the last centuries, industrial processes have evolved immensely. Advances in power and technology significantly impacted the manufacturing process over time and revolutionized the industry. The industry has gone through four revolutions shown in Figure 1.

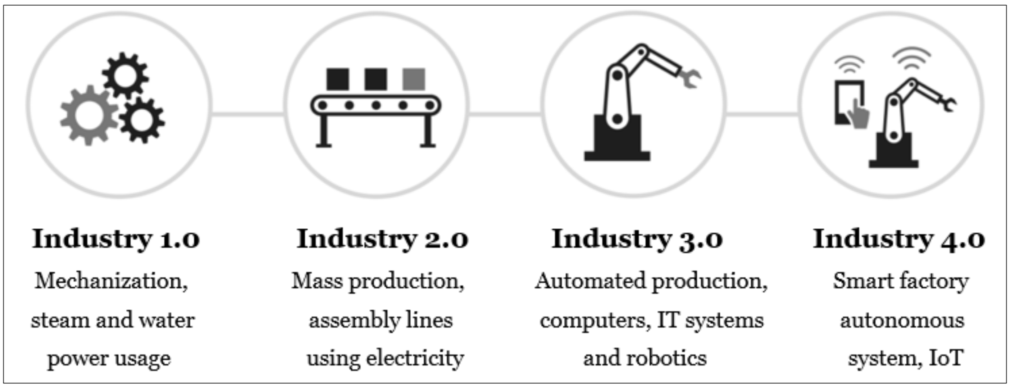

Figure 1. Four Industrial Revolutions
Source: (Meloeny, 2022)

1st Industrial Revolution

The First Industrial Revolution began in the 18th century through the use of steam power and the mechanisation of production. The use of it for industrial purposes helped to increase productivity. More efficient production subsequently reduced prices for products, primarily due to lower labour costs. For example, rather than employing people to power weaving looms, steam engines were used to provide power for the machines. Other machines invented during this period include the water wheel, more complex spinning wheels and the steam engine (Shutt, 2021).

2nd Industrial Revolution

The Second Industrial Revolution began in the 19th century through the discovery of electricity and assembly line production. The use of electricity made it possible for many industries to incorporate modern production lines and carry out mass production. Henry Ford was the first that brought the idea. He applied the principle of mass production into automotive from a slaughterhouse, where pigs hung from conveyor belts and each butcher performed only a part of the task. Before one station assembled an entire automobile, then the vehicles were produced in partial steps on the conveyor belt.

3rd Industrial Revolution

The third industrial revolution began in the 20th century, around the 70s through partial automation using computers and Programmable Logic Controllers (memory-programmable controls). It is a move from mechanical and analogue electronic technology to digital electronics. Thanks to these technologies it is able to automate an entire production process without human assistance. Examples are robots that perform programmed sequences without human intervention (Soldatos et al., 2022).

4th Industrial Revolution

Currently, we are on the threshold of the 4th industrial revolution often called Industry 4.0. It builds on the developments of the 3rd industrial revolution as next step to production automation. Production systems with computer technology are expanded by a network connection and have a digital twin on the Internet. The networking of the systems leads to „cyber-physical production systems", that allow building smart factories where production systems, components, products, and people communicate via a network and production is nearly autonomous. It increases production efficiency, reduces costs and saves resources (Castagnoli et al., 2022).

1.2. Definition of Industry 4.0

The term Industry 4.0 was used for the first time in 2011 at the Hanover Fair in Germany in relation to the initiative to enhance German competitiveness in the manufacturing industry. It has ignited a vision of a new Industrial Revolution. Since then, it has spread and many similar initiatives in other countries have been developed and several definitions of Industry 4.0 were presented in academic and non-academic sources.

The Final report of the *Industrie 4.0 Working Group* - **Recommendations for implementing the strategic initiative Industrie 4.0** defines the essence of Industry 4.0 as: „technical integration of Cyber-Physical Systems (CPS) into manufacturing and logistics and the use of the Internet of Things and Services (IoT) in industrial processes" (Kagermann et al., 2013)".

Some other definitions explain CPS in more detail at three levels as physical objects; data models of physical objects in a network infrastructure; and services based on available data (Drath & Horch, 2014). According to Javaid et al. I4.0 is an "integration of complex physical devices and machines with networked sensors and software aiming to predict, control and plan for better business" (Javaid et al., 2021). CPS and the IOT most often appear in definitions as the key elements that enable the creation of interconnected, intelligent production systems enabling self-regulation and self-optimization. They contribute to the transition from centralized production towards flexible and self-controlled. Smart Factory is the concept defining the future state of a fully connected manufacturing system, mainly operating without human force using a constant stream of data from connected operations and production systems to learn and adapt to new demands. Other related technological enablers of Industry 4.0 and Smart Factories are Big Data (BD), Cloud Computing (CC), Artificial Intelligence (AI), Virtual and Augmented Reality (VR, AR), Advanced Robotics, Additive Manufacturing, Cybersecurity. (Benotsmane et al., 2019). The above-mentioned technologies are interdependent, e.g. many of the analytical capabilities implied by CPS and the IoT are provided by data processing technologies, often offered as service applications delivered through Cloud Computing; Advanced Robotics leverage Artificial Intelligence, etc.

Besides the technological elements of Industry 4.0, there are definitions highlighting the influence of technologies on the structure of the organization, cooperation with partners and managing the entire value chain e.g. I4.0 is "the new model of value chain management throughout the product lifecycle, and a collective term for technologies and concepts of value chain organization" (Saucedo-Martínez et al., 2018).

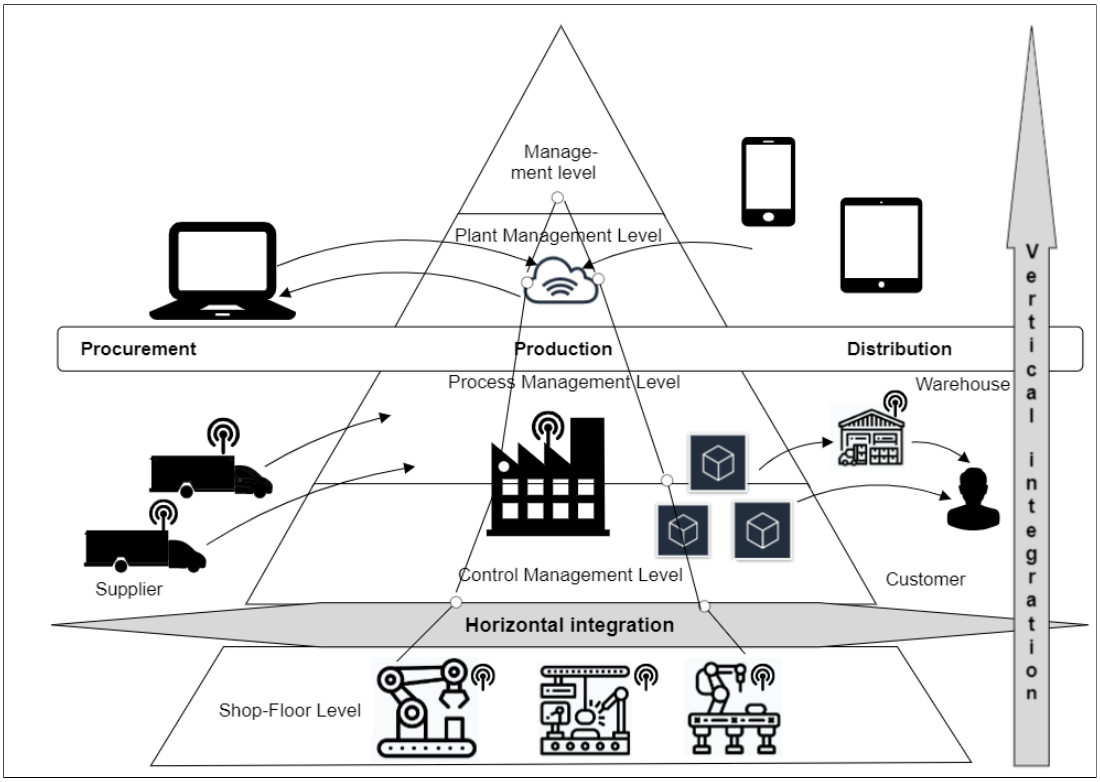

Figure 2. Vertical and Horizontal Integration
Source: own elaboration.

The definitions outline usually some or all the three features of Industry 4.0 (Kagermann et al., 2013; Stock & Seliger, 2016):

- horizontal integration across the entire value creation network,
- vertical integration and networked manufacturing systems,
- end-to-end engineering across the entire product life cycle.

The vertical and horizontal integration is shown in Figure 2. Horizontal integration refers to the integration of IT systems, processes, resources, and information flows between the organization and interested parties (suppliers, other organizations, customers) while vertical integration concerns the integration of these elements through the departments and hierarchical levels of an organization. These two types of integration aim to deliver an end-to-end solution across the entire value chain.

Industry 4.0 represents the further developmental stage in the management of the entire value chain in the manufacturing industry (Deloitte, 2015). The above-mentioned features enable flexible and dynamic management of complex systems and enable all players in the value chain to be digitally connected, achieving mass customization and demand-driven supply chain services. According to Gabriel & Pessl "Industry 4.0 represents a fundamental paradigm shift towards individualized production that will enable new business models and online services" (Gabriel & Pessl, 2016). Industry 4.0 from the busiess model innovation perspective is reflected by several definitions, e.g. (Frank et al., 2019; Ibarra et al., 2018; Reinhard et al., 2015). The development of new business models is driven by customer needs and mass customization requirements and enabled by innovative technologies.

According to the study by Nosalska et al. the most frequent terms accompanying Industry 4.0 are Value Chain, CPS, IoT, Smart Factory, Intelligent Technologies (like AI, BD, CC, etc.), Business Models, Customization, and Smart Product (Nosalska et al., 2019).

Among the main principles for the development and deployment of Industry 4.0 the following appear the most frequently (Pereira & Romero, 2017):

- Interoperability – communication and data exchange between objects, machines, people,
- Virtualization – digital reflection of the physical environment,
- Decentralization – CPS with decision-making capabilities,
- Real-time capability – real-time data allowing immediate decisions,
- Service orientation – product extension with services,

- Modularity – dynamic configuration of the various elements of business processes.

Definitions, which have been published explain the I4.0 term by listing its characteristic elements. Industry 4.0 involves a broad set of technological and business aspects. These are interdependent and their impact on organizations should be regarded as the influence of a set of intertwined factors. Creating a concise definition that includes all of the Industry 4.0 organizational capabilities and relevant aspects remains difficult as the concept includes a wide range of issues.

1.3. Industry 4.0 Maturity Models

In general, the term "maturity" refers to a "state of being complete, perfect, or ready" and implies some progress in the development of a system. The concept of maturity incorporates the notion of gradual evolution through intermediate stages. Maturity Models (MM) are generally used as tools to conceptualize and measure the maturity of an organisation or a process regarding some specific target state. MM can be useful and help to guide organizations on the way to I4.0 excellence (Sütőová et al., 2020). The I4.0 MM can be used in each phase of digital transformation to help identify where there are gaps, establish key areas to focus on, and where to start (Deloitte, 2018).

Several Industry 4.0 Maturity Models have been published by academics and consulting companies (e.g. BCG, Pwc, McKinsey & Company) with varying scopes or dimensions and metrics for measuring success. Among the first models that were developed belongs the **Industry 4.0 Maturity Model** published by the National Academy of Science and Engineering (acatech). The model's approach is based on a succession of maturity stages that help companies navigate their way through every stage in the transformation, from the basic requirements for Industry 4.0 to full implementation. The six maturity stages from computerisation and connectivity up to adaptability allowing a company to delegate certain decisions to IT systems are shown in Figure 3. Four organization structural areas of *resources, information systems, culture and organisational structure* are assessed. Necessary capabilities are defined for each structural area. The identification of the current I4.0 maturity stage is based on the I4.0 capabilities. The capabilities are determined on the basis of the processes in the functional areas – *development, production, logistics, services and marketing & sales* that are assessed. The model helps to develop a digital roadmap tailored to the needs the of organization (Schuh et al., 2017).

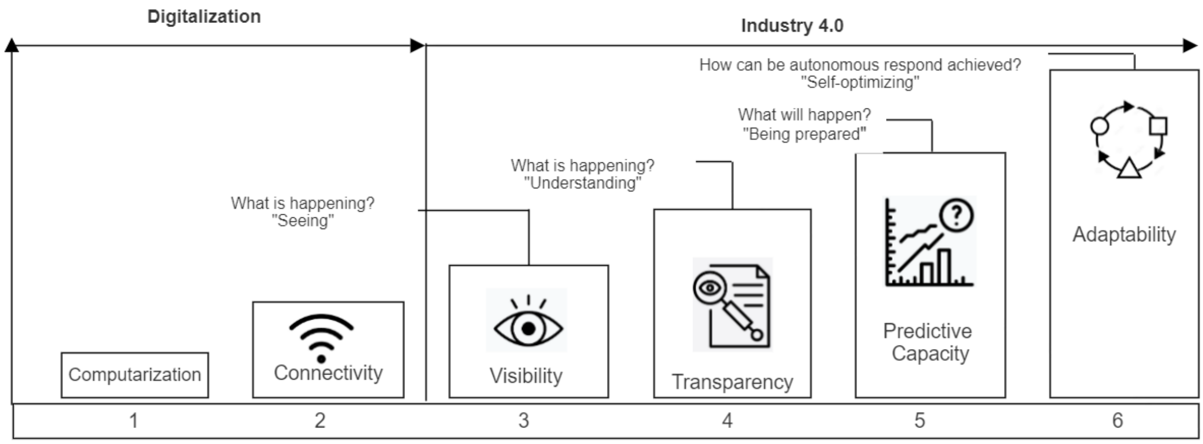

Figure 3. Industry 4.0 Maturity Stages
Source: (Schuh et al., 2017).

The examples of other selected I4.0 maturity or readiness models are:

- **Digital Compass** developed by McKinsey & Company consists of eight basic value drivers (dimension) and 26 practical Industry 4.0 elements. *Quality* is one of the direct drivers represented by the elements like Digital quality management, Advanced process control and Statistical process control. Other drivers in the model are *Supply/Demand Match, Time to Market, Service/After-sale, Resources/Processes, Asset Utilization, and Labour* (McKinsey & Company, 2015).
- **Industry 4.0 Readiness Model** developed by Impuls Foundation of the German Engineering Federation measures Industry 4.0 on the 7 levels of readiness. The model consists of 6 main dimensions and related 18 elements. The main dimensions are *Strategy and organization, Smart factory, Smart operations, Smart products, Data-driven services, Employees*. It allows self-assessment and calculation of the I4.0 scorecard. It helps to identify areas that need improvement (Impuls, 2015).
- **Industry 4.0 Maturity Model** developed by Schumacher et al.. The model is formed by 9 dimensions and 62 elements. The main dimensions are *Strategy, Leadership, Customers, Products, Operations, Culture, People, Governance, Technology* (Schumacher et al., 2016). The evolution path of each element undergoes five maturity levels (Schumacher et al., 2016).
- **Digital Readiness Assessment Maturity Model (DREAMY)** developed by De Carolis et al. defines 5 main functional areas: *Design and Engineering, Production Management, Quality Management, Maintenance Management,*

Logistics Management. Quality Management is represented by two elements – Product testing and Quality management in production. The readiness is assessed by the measurement instrument defining 5 levels of readiness. The above-mentioned areas are assessed in the context of 4 dimensions, which are part of the model: process; monitoring and controlling; technology; organization (De Carolis et al., 2017).

- **Industry 4.0 Maturity Model** developed by Santos & Marinho consists of five main dimensions - *Organizational Strategy, Structure and Culture, Workforce, Smart Factories, Smart Processes, Smart Products and Services*. Every dimension is characterized by capabilities that are assessed by using 6 maturity levels (Santos & Martinho, 2019).

There are also other I4.0 maturity models developed by academics or consulting organization, e.g. (Deloitte, 2018; Klötzer & Pflaum, 2017; PwC, 2019). These models are so-called holistic models that enable to assess and utilize elements of I4.0 from all perspectives and hence derive encompassing success factors. There are also MMs focusing on the specific areas of I4.0 application or a limited number of aspects related to I4.0 such as logistics, supply chain, information technologies, etc. (Sütőová et al., 2020).

Chapter 2. Industry 4.0 Policies and Initiatives on the Level of EU and Visegrad Countries (Czech Republic, Poland and Slovakia)

2.1. Industry 4.0 Policies and Strategies at the EU Level

European Union published an ambitious strategy for creating a **Digital Single Market (DSM)** in 2015. The DSM strategy, especially the pillar on „Maximising the Growth Potential of the Digital Economy", contains all the major levers for improving industry digitization with actions in areas such as the data economy, IoT, cloud computing, standards, skills, and e-government (European Commission, 2016).

The first EU industry-related initiative **Digitizing European Industry (DEI)** was launched within the Digital Single Market package in April 2016 by the European Commission. Its aim is to reinforce the industrial and innovation pillar of the DSM strategy. The Initiative's objective is to ensure that every business (all sizes, locations and sectors) in Europe can fully benefit from digital innovation (European Commission, 2018b). Commission aims is to support Member States in developing and implementing their own digitalization strategies. Action lines of the DEI are: European platform of national initiatives, Digital innovation hubs, Partnerships and industrial platforms, Regulatory framework fit for the digital age and preparing Europeans for the digital future.

One of the key pillars of the DEI are the so-called *Digital Innovation Hubs (DIH)*. The DEI activities were planned to be founded through the European Fund for Strategic Investments (EFSI), Horizon 2020, and the European Structural and Investments Funds (ESIF) (Propris & Bailey, 2020). The plan was to mobilise 50 billion euros of public and private investment until 2020. For the EFSI funds, since the DEI initiative was launched halfway through the 2014-2020 programme period, there was no legal requirement for Member States to monitor projects relevant to the DEI initiative. Therefore, according to the European Court of Auditors the data collection arrangements in most Member States do not capture information about the DEI initiative, preventing monitoring at Member State and EU level (European Court of Auditors, 2020). According to the *EU Smart Specialisation Platform*, 14 DIHs operating in Czech Republic, 23 DIHs in Poland and 5 DIHs in Slovakia (European Commission, 2020).

In 2018, the European Commission proposed for the 2021-2027 period the first **Digital Europe Programme**, a regulation with a budget of € 7.5 billion with the aim to contribute to the DEI initiative. It provides funding in 5 areas: supercomputing, artificial intelligence, cybersecurity, advanced digital skills, and ensuring a wide use of digital technologies across the economy and society (including through Digital Innovation Hubs). This budget will be in addition to the other funding available for the digitalising industry for the 2021-2027 period, such as Horizon Europe and the ESIF (European Court of Auditors, 2020). It is planned to allocate about 10 % of the funding to *European Digital Innovation Hubs (EDIH).* There have been established 5 EDIHs in the Czech Republic as well as in Slovakia and 11 in Poland. EDIH funded under the Digital Europe programme are co-funded by the European Commission and by Member States/associated countries. There is also another type of structure named ,"Seal of excellence EDIH" and they have been positively evaluated in a European competitive call, but is funded only by national or regional budget (European Commission, 2020).

In 2020, the European Council and the Commission presented a **Roadmap for Recover**y from the coronavirus outbreak to the Parliament, with the ultimate objective of building a more resilient, sustainable and fair Europe. This plan cites digital transformation, alongside the Green transition, as having a priority role in relaunching and modernizing the economy.

In 2014, the European Commission introduced the **Digital Economy and Society Index (DESI)**, a composite index to monitor the digital progress of Member States. It consists of The DESI s five main dimensions: Connectivity, Human Capital, Use of internet services, Integration of Digital Technology, Digital Public Services. The most relevant dimensions for digitalizing European industry are Connectivity, Human Capital and the Integration of Digital Technologies. The latest edition of DESI was published in July 2022, where Poland, Czech and Slovak Republic are under the EU average. The Czech Republic is in the 19th place, Slovakia in the 23rd place and Poland in the 24th place (European Commission, 2022).

According to the *International Federation of Robotics* report presenting the robot density – a barometer to track the degree of automation adoption in the manufacturing industry around the world and measures the number of robots per 10,000 workers in the industry. Europe average is 123 units and the most automated country is Germany (4th worldwide with 371 units in 2020). In Slovakia the result was 175 robots per 10,000 workers in the industry, in the Czech Republic it was 162 and in Poland 52 robots (IFR, 2018).

2.2. Industry 4.0 Initiatives in the Czech Republic

In September 2015, the Ministry of Industry and Trade of the Czech Republic issued the **National Initiative Industry 4.0**. This document was the initial initiative to describe the technological prerequisites and the current state of the Industrial Revolution in the Czech Republic and the possible pitfalls that the Industrial Revolution may bring with it. With an emphasis on the security and reliability of systems with the preservation of data privacy and intellectual property rights. An important part was a reflection on the emerging requirements for applied research in the Czech Republic as well as the impact on changes in the Czech educational system so that future graduates find applicability in the innovative world of work, which is changing comprehensively. The document concludes with a roadmap for the Czech Republic and an action plan containing individual plans for supporting the implementation and development of Industry 4.0 in the conditions of the Czech Republic (Ministry of Industry and Trade of Czech Republic, 2016a). In connection with compliance with the set action plan, the Government of the Czech Republic subsequently approved the National Initiative Industry 4.0 in 2016, which was elaborated on and submitted by the Ministry of Industry and Trade. The long-term goal of this initiative is to maintain and strengthen the competitiveness of the Czech Republic in the era of the fourth industrial revolution. The document aims to provide sufficient information for stakeholders with the idea of rapid formulation of concrete economic, political and social objectives and proposal of action measures responding to the ongoing changes caused by the technologies of the fourth industrial revolution (Ministry of Industry and Trade of Czech Republic, 2015)

Specifically, within the area of automotive production in the Czech Republic, the document **Action Plan for the Future of the Automotive Industry in the Czech Republic - „Czech Automotive Industry 2025"** was created in 2017. The plan deals with three areas, namely electro-mobility, autonomous vehicles and digitalization. A total of 25 measures have been proposed within the plan, which mainly concern infrastructure for emission-free vehicles, standardization and legal aspects of automated driving, high-speed internet, digital and mobile services and research and development for the automotive industry. To achieve the objectives, it will be necessary to adapt the relevant grant titles to support science, research and innovation and to ensure a change in the education system (Government of Czech Republic, 2017).

In 2016, *Industry Cluster 4.0* was founded, which represents an association of engineering and technology companies. The purpose of the cluster is to strengthen the competitiveness and innovative activities of companies, especially through the implementation of the concept of „Industry 4.0" (Ministry of Industry and Trade of Czech Republic, 2016b)

The *National Centre for Industry 4.0* was established in 2017 as a technology-neutral and open academic-industrial platform. The Centre connects innovation leaders, manufacturing and technology companies, universities, research and industry organizations with the state and the media, helping to create an optimal environment for a sustainable future. The Centre's areas of activity include Technology Vision, Education Support, Outreach, Support for Collaborative Projects (National Centre Industry 4.0, 2019). Many universities are partners of the Centre. In the field of Industry 4.0, the Centre is involved in a number of national and international projects (National Centre Industry 4.0, 2017)

The *Confederation of Industry of the Czech Republic* has been focusing on the topic of Industry 4.0 for a long time. For three years now, it has announced the competition „Industry 4.0 Award" and defined „**Priorities and requirements for the digital economy, Industry 4.0**", e.g. for 2022, in the framework of the Programme Statement (Confederation of Industry of the Czech Republic, 2023).

The *Czech-Moravian Confederation of Trade Unions*, within the framework of the project „§ 320a ZP I. - Industry, Education, Work, Society 4.0" from 2017, developed, among others, the teaching texts „Industry 4.0, Education 4.0, Work 4.0 and Society 4.0".

The *Ministry of Labour and Social Affairs* is focusing on Work 4.0 as part of its analytical and conceptual work. The **Work 4.0 Initiative** and the **Work 4.0 Action Plan** have been developed (Ministry of Labour and Social Affairs of the Czech Republic, 2016)

Actions from the Work 4.0 Action Plan are incorporated into the **Action Plan for Society 4.0** (Government Office of the Czech Republic, 2017). The Action Plan for Society 4.0 was developed by the *Society 4.0 Alliance*, which was established in 2017. The Alliance was established to take a comprehensive approach to Society 4.0 and to coordinate the digital agenda at the national level. The Action Plan is the overarching document of the Czech government for the digital agenda and the so-called Society 4.0. The material summarizes the direction of government policy and key government measures to support the development of the digital market in the Czech Republic. At the same time, it formulates other priority tasks set by the government in the context of the societal challenges related to the impact of the introduction of digital technologies on the economy and society – the so-called fourth industrial revolution.

2.3. Industry 4.0 Initiatives in Poland

Digital Poland Programme 2014-2020 focused on strengthening digital foundations for national development. It was financed from two sources: the European Regional Development Fund, from which €2,172.5 million is allocated to the programme and national funds - public and private, with a minimum commitment of €394.4 million (Ministry of Development Funds and Regional Policy, 2023).

The **European Funds for Digital Development (FERC) 2021-2027** in Poland is a continuation of the Digital Poland 2014-2020 Program and is the next stage of the digital transformation of the country. The scope of support under the Program is complementary to the support of other programs implementing the objectives of the cohesion policy for 2021-2027 and other national and EU instruments. The budget is approx. €2 billion. The scope and main objectives include: building a gigabit society in Poland, increasing access to ultra-fast broadband internet, providing access to advanced e-services allowing for fully electronic settlement of affairs of citizens and entrepreneurs, ensuring cyber security through support under the new dedicated area of intervention, development of the economy by increasing the amount of high-quality data open for re-use, development of cooperation to create digital solutions to socio-economic problems, support for the development of advanced digital competencies of staff involved in the provision of digital services, products or processes, in particular in the area of cyber security (Ministry of Development Funds and Regional Policy, 2021a).

The European Funds for Modern Economy 2021-2027 program is a continuation of the two previous programs. The budget is approx. €7.9 billion. The main objectives include: increasing research and innovation capacity and the use of advanced technologies, increasing the competitiveness of SMEs, developing skills for smart specialization, industrial transformation and entrepreneurship, transformation of the economy towards Industry 4.0 and green technologies. The program consists of four priorities: support for entrepreneurs, innovation and friendly environment, greening of enterprises and technical assistance. An assumed form of support are subsidies, financial instruments, capital and guarantee, instruments combining repayable and grant financing (Ministry of Development Funds and Regional Policy, 2021b)

Future Industry Platform Foundation (FPPP) was founded in 2019. The Industry Platform is currently under the supervision of the Ministry of Development Funds and Regional Policy of the Future. It was established to strengthen the competencies and competitiveness of enterprises operating in Poland by supporting their transformation towards Industry 4.0. FPPP works to strengthen the business ecosystem created by Polish manufacturing companies. They achieve this goal by creating mechanisms for cooperation, knowledge sharing and building trust in relations between market entities involved in the digital transformation process (Ministry of Economic Development and Technology, 2019).

Polish Agency for Enterprise Development (PARP) is involved in digital transformation. Agency's objective is to implement economic development programs supporting the innovative and research activities of small and medium-sized enterprises (SMEs), regional development, export growth, human resources development and the use of new technologies in economic activity. PARP is involved in the implementation of national and international projects financed from the structural funds, the state budget and long-term programs of the European Commission (Polish Agency for Enterprise Development, 2018).

The *National Center for Research and Development (NCRD)* is an executive agency within the meaning of the Act of 27 August 2009 on public finance, supervised from 1 August 2022 by the Minister of Development Funds and Regional Policy (Ministry of Science and Higher Education, 2022). The main task of the National Center for Research and Development is to manage and implement strategic research and development programs that directly translate into the development of innovation.

In Poland 15 *DIH*s have been established. The youngest DIH is DIH4.AI and it was founded in 2019 in Gdansk. DIHs are mainly located in large cities such as Warsaw, Cracow, Wroclaw, Gdańsk, Poznań, Lublin. The main area of activity is mainly national, but there are DIHs such as the Centre for Advanced Manufacturing Technologies, Wroclaw University of Science and Technology European ones. According to the EU data, 11 *EDIH*s in Poland have been established (European Commission, 2020). Polish Agency for Enterprise Development (PARP) organizes competitions under the European Funds for Modern Economy (FENG) program –"Co-financing of EDIH activities". Funding may cover activities offered by EDIH, such as: verification of the company's digitization capacity and its demand for technologies in this area, development of a digital transformation plan, improvement of competencies and access to current specialist knowledge, as well as creating conditions for testing solutions or experimenting with the latest technologies that are potential of key importance to the company's products, services, processes or adopted business models based on digital solutions. The total amount of support provided under the "Co-financing of EDIH activities" for 2023 is PLN 245 million (Polish Agency for Enterprise Development, 2023).

2.4. Industry 4.0 Initiatives in Slovak Republic

In 2016, the Ministry of Economy of the Slovak Republic published the **Concept of Smart Industry for Slovakia**, the nationwide initiative to transform and strengthen the industry and help Slovakia to adapt to Industry 4.0 related changes (Ministry of Economy of the Slovak Republic, 2016). It is further built upon the Strategy for Smart Specialization of the Slovak Republic (RIS3), particularly in Research and Development (R&D).

Arising from the concept, the *Smart Industry Platform* was formed as a first step in the implementation of the overall initiative, as a working group of multidisciplinary experts from industry, academic and government, who actively contributed to the drafting of the **Smart Industry Action Plan for Slovakia** (Ministry of Economy of the Slovak Republic, 2019). The action plan provides a set of 35 measures with the implementation by the end of 2020. The following priorities were defined in the action plan: Research, development and innovation, Basic principles of IT security of smart industry implementation, Labour market and education, Reference architecture, standardization and creation of technical standards, European and national legal framework conditions, Information and promotion.

No specific budget was allocated for Smart Industry initiatives. The measures in the action plan were planned to be financed either through the European Structural and Investment Funds (ESIF) or the national budget (European Commission, 2018a). Among the activities that have been realized are the establishment of the *Industry 4UM digital platform*, development of the **Act on cyber security and amendments to certain laws**, establishment of the *Dual Education Platform, Digital Coalition* (to mobilize public, private, academic and civic organizations and institutions in Slovakia to improve the digital skills), creation of the *Learning for the 21st-century training platform,* creation of *4 DIH*, etc. (Wik Consult & VVA, 2019).

At the end of 2018, the Office of the Deputy Prime Minister for Investment and Informatization presented a **Digital Transformation Strategy of the Slovak Republic 2019 - 2030.** It is a cross-sectional government strategy that defines the policy and particular priorities of Slovakia in the context of the currently ongoing digital transformation of the economy. The strategy defines the following areas: Economy, Society and Education, Public Administration, Territorial Development and Science Research and Innovation. The strategy works with the existing strategies and action plans like Smart Industry Action Plan for Slovakia. The strategy puts primary emphasis on current innovative technologies such as Artificial Intelligence, Internet of Things, 5G Technology, BD and Analytical Data Processing, Blockchain and High-Performance Computing that will become the new engine of economic growth and competitiveness. The strategy covers priority areas for short–term (3Q/2019 –2Q 2022) and long-term (3Q 2022 -2030) horizons (Ministry of Investments, Regional Development and Informatization of the Slovak Republic, 2019a).

Action Plan of the Digital Transformation of Slovakia 2019-2022 contains 7 horizontal measures aimed at building the institutional background and increasing Slovakia's innovative performance, including strengthening the ability to use new EU digital funds. Other key measures are divided into four strategic goals. They cover all areas of the vision of Slovakia's digital transformation declared in the strategy. The funding of measures is tied to the 2014-2020 program period (Ministry of Investments, Regional Development and Informatization of the Slovak Republic, 2019b).

The examples of activities that have been realized are the establishment of *5 EDIH* in Slovakia that help businesses and organizations in introducing innovations and using advanced technologies; the creation of the *AISlovakia* national platform for the development of artificial intelligence allowing cooperation of the academics with representatives of employers, government, international institutions or with individuals with the aim to develop the potential of artificial intelligence; establishment of the *National Supercomputing Centre*, which supports and covers all high computing activities in Slovakia; *Competence and Certification Centre for Cyber Security* - for coordination, education, conformity assessment and expert activities in cyber security.

Action Plan of the Digital Transformation of Slovakia 2023-2026 was approved by the government in 2022. The priority areas are the Digitization of a Wider Economy, Digital Infrastructure, Supporting the Potential of Artificial Intelligence, and Digital Society (Ministry of Investments, Regional Development and Informatization of the Slovak Republic, 2022). Activities have been financed from the European Structural and Investment Funds as well as directly managed EU funds (Digital Europe Programme, Horizon Europe or other financial instruments) and the national budget. In the Slovak recovery plan, 20% (1,3 mld. €) of the total budget is allocated to measures that will support the country's digital transformation (Ministry of Finance of the Slovak Republic, 2021).

In 2021 the government of the SR approved the **Strategy and Action Plan for Improvement of Slovakia's Position in the DESI index** until 2025 as a response to the ongoing trend in the stagnation of the evaluation of SR in DESI. As it was mentioned above, Slovakia is under the EU average and is in 23rd place. The strategic priority areas are Connectivity, Human Capital, Utilization of the Internet, Integration of Digital Technologies, and Digital Public Services. The Digital Transformation Strategy and action plans of the Slovak Republic contribute to the improvement of the position of the Slovak Republic in DESI (Ministry of Investments Regional Development and Informatization of the Slovak Republic, 2021).

Chapter 3. Quality 4.0 as a Part of Industry 4.0

3.1. Quality Evolution Towards Quality 4.0

I4.0 impacts all functional areas of business. In the context of I4.0, the concepts and terms like Marketing 4.0, Human Resource 4.0, Supply-Chain Management 4.0, Logistics 4.0, Maintenance 4.0, Manufacturing 4.0, Quality 4.0 has emerged.

Quality models and practices went through various development stages from Statistical Quality Control (SQC) through Quality Assurance (QA) to Total Quality Management (TQM), which were affected by technological development. The onset of Industry 4.0 and the utilization of smart technologies advanced quality management practices and a new concept – Q4.0 has appeared, which represents a new development stage of quality management. Figure 4 shows the four development stages of quality with characteristic features.

Figure 4. Evaluation of Approaches to Quality
Source: own elaboration.

Q4.0 is an integral part of the I4.0 movement. According to American Society for Quality, "Q4.0 brings together I4.0's advanced digital technologies with quality excellence to drive substantial performance and effectiveness improvements" (ASQ, 2020). It is a new way for quality practitioners to handle quality and learn how they use and achieve excellence through quality using today's digital technologies. "Q4.0 is the use of advanced technologies to design, operate and maintain adaptive, predictive, self-corrective, automated quality systems along with improved human interaction through quality planning, assurance, control and improvement to achieve new optimums in performance, operational excellence and innovation to meet goals of an organization" (Antony et al., 2022).

Quality 4.0 integrates I4.0 features with traditional quality management practices, but it doesn't replace traditional methods and tools of quality management, rather builds upon them and improves them. Even though Q4.0 is fuelled by technology, success requires a multifaceted approach that addresses the full range of strategic, cultural and already mentioned technological issues. Among the main principles of Q4.0 belong (Graham, 2022):

- Cyber-Physical Systems,
- Co-creation of value,
- Transparency and collaboration,
- Mutual trust,
- Rapid adaptive learning,
- Data value,
- Technology and combined intelligence.

These principles help to enhance the basic 7 quality management principles and implement them more effectively.

3.2. Quality 4.0 Features

Industry 4.0 integrates smart technologies and offers many opportunities for the field of quality management. Smart technologies, horizontal and vertical integration brings many benefits like improved quality, efficiency, customer satisfaction and innovation. The impact of I4.0 on quality management can be summarized as follows:

Supply chain

The integration of the entire value chain allows a higher level of collaboration and transparency among all parties in the supply chain. Suppliers can be connected and involved in the manufacturing process, quantities of materials, defects, and problems due to supplier quality issues can be traced and reported to suppliers in real-time. Real-time data that are captured at different locations in the value chain, can be streamed back to all involved parties (from product design to final delivery and operation). Shared information will help to track and to resolve quality issues, standardise quality practices, and improve performance. Blockchain technology enables tracking of product history (origin, production line even operator) and quality especially when supply chains are deep and versatile (Sader et al., 2022).

Research and Development (R&D)

Horizontal integration allows R&D activities to be extended and involve stakeholders in design. Also, through end-to-end integration data pertaining to the usage of the product can be relayed back to the designers (Sony et al., 2020). Customer needs can be better mapped and better products and services can be designed. New collaboration platforms facilitate communication with customers and make understanding market and customers' attitudes better.

Digital twins improve pre-production tests, by virtually simulating the products' testing ensuring high quality in the design and manufacturing process before execution (Kupper et al., 2019). End-to-end data used for simulations enable optimize parameters selection for products as well as optimize processes. Digital twins help to reduce the need for costly physical prototypes and shorten time-to-market. They improve all the phases of product design and development.

Planning

By applying BD analytics to planning, an organization can improve its ability to forecast the production it requires. It helps to understand market demands and supplier capacity levels and lead times. Data can be analysed to uncover demand patterns, track movements of products through the supply chain, and understand what customers want, and where—so better planning can be realized to provide products at the right time and place (Sniderman et al., 2016).

Production and Inspection

The smart factory organizes itself and can produce based on individual customer requirements and changes in supplies. The physical and informational subsystems are integrated at various levels (vertical integration) to create a flexible and reconfigurable manufacturing system to minimize downtime. Manufacturing processes are possible trough self-regulation and self-optimization thanks to advanced BD analytics. Each step in the production process will be fine-tuned in real-time based on an ongoing analysis of the outcomes of previous production steps and product requirements. I4.0 enables deployment of automated inspection systems that use Artificial Intelligence. It can reduce manual work and ensure the speed of the inspection matches the production speed. It can identify operator errors, quality deviations, and process variations in real time and link product defects with process inaccuracy, and root causes.

Decision-making

Availability of data in real time (from processes, assets and product data) advanced data analytics help to support decision-making and continuous improvement. Quality indicators are displayed at every level of management, at every stage of production, and for every function at the organization. Q4.0 stresses the importance of prescriptive analytics compared to descriptive or predictive that help recommend optimal action. Digital Twin allows to make accurate predictions of how a product or process will behave in the future.

Analytics algorithms can provide two levels of human intervention for decision-making. The first level of intervention is the decision support system. For instance, when algorithms provide recommendations for quality of design, quality improvement. The larger solution set from these algorithms will warrant human intervention in an assisted manner to finalize the best options. The second level of prescriptive analytics will be based on intelligent algorithms which will result in decision automation through machine learning. This type of prescription algorithm will help in implementing the prescribed action in an automated and self-regulating manner. Prescriptive analysis algorithms in terms of the first level will be very beneficial in quality planning and quality improvement, as they will provide a large amount of solution options. Prescriptive analysis in terms of decision automation will be more helpful for quality control, because decisions such as conformance to specifications can be automated by analysing data (Sony et al., 2020).

Service and after-sales

The product in use can communicate data regarding its condition to its manufacturer in real time. By analysing the data, the manufacturer can generate insights that serve as an early warning of potential breakdowns that could trigger warranty costs. A manufacturer can also enhance customer support by remotely diagnosing quality issues. Manufacturers can store field data centrally and use an AI system to identify potential failures before they occur, enabling their technicians to fix problems before a breakdown.

3.3. Quality 4.0 Tools

Quality 4.0 leverages intelligent technologies to achieve a high-level of quality, greater efficiency of processes, enhanced customer satisfaction and faster innovation. Intelligent technologies make it easier for quality teams to access data from different sources and get critical insight within large data sets and extract valuable information.

According to American Society for Quality; Radzwill Quality 4.0 tools includes Enabling technologies (sensors, actuators, IoT CC, VR, AR); BD; Blockchain; Deep learning; Machine learning; AI; Statistics and Data Science. AI encompasses Machine Learning and Neural Networks (ASQ, 2020; Radziwill, 2018).

IoT

IoT is a network of physical objects with embedded sensors, software and other technologies (CPS) to collect and exchange data via the internet in real time. The examples of IoT are intelligent objects, systems, products, robots, etc. IoT connects the real and virtual world and enables the transfer of data between objects and people in real time. IoT facilitates real-time monitoring of products, equipment, and production processes as well as control of processes and equipment remotely. It helps to accelerate response time. IoT also provides better visibility into the flow of materials and products. IoT is key enabler for the creation of digital twin. The digital twin is a virtual representation of the real world – a product, process, asset or system using historical or real-time data. It utilizes also other intelligent technologies and it is an important tool of Q4. 0.

Big data

Big Data refers to large sets of structured or unstructured data that can provide valuable insights when are analysed with the right software and tools. IoT is considered the major source of BD. Typical for BD is their volume, variety and velocity. Conventional storage and statistical analysis are inefficient, BD requires powerful technologies and advanced machine learning and AI algorithms. The mining of knowledge from BD enables effective decision-making and creates value within the company (Qi & Tao, 2018). Not only internal data, but also data about customers, suppliers and other external stakeholders are used. Data and information extracted from the data are crucial for effective quality management. They play an important role in quality planning and improvement. BD challenges include their capturing, storing, searching, sharing, analysing, visualizing and securing. The type of BD analysis can be descriptive – generation of information; diagnostic – pattern recognition; predictive – forecast; prescriptive analytics – decision making.

Cloud Computing

CC provides basis for IoT and other technologies. IoT generates lots of data from various objects and processes. CC delivers services like servers, storage, networking, applications, analytics, software, platforms over the internet. IoT and CC facilitate remote monitoring and control, enabling organizations to data and manage quality across different departments, locations, and supply chains. Real time automated collection and sharing of the right data to the right people and objects is key to effective decision-making and accelerating time to action. It enables to manage quality across different locations and supply chains. CC is seen as a way to support collaboration, help manufacturers align business strategies and product innovation and create smart networks (Msakni et al., 2023).

Virtual and Augmented Reality

VR is a technology that provides users with a simulated experience of a virtual environment. AR is defined as the technology in which virtual objects are blended with the real world and interact with each other (Pelin Yildiz, 2022). VR and AR support a human-centred environment. Application areas include, e.g.:

- visualization of various work instructions that guide workers through standardized processes. In the case of maintenance issues, the user can visualize step-by-step procedures in real time through augmented reality from experts with remote assistance systems to solve lack of critical knowledge (Etonam et al., 2019),
- layouts and workplace design to ensure effective material and workflow and setting-up workstations ergonomically,
- product design and prototype testing enabling cost reduction,
- training and development of employees' competencies,
- collaboration and communication enhancement among remote teams.

Digital twin (DT) provides a broader application space for virtual reality and at the same time puts higher requirements for the technological progress of virtual reality. Digital twin and VR provide a co-simulation environment that can enhance experimentation. E.g., digital twin lacks realism for human-centred design of manufacturing process and workstation, gives new insights into product design and prototype testing, etc.

Machine learning and Deep learning

The capacity of systems for advanced problem-solving, generally termed AI, is based on analytical models that generate predictions, rules, answers or recommendations (Janiesch et al., 2021). AI within Quality 4.0 is used primarily to support humans in decision-making, and automate processes with adaptive and learning capabilities.

Machine learning is a subset of AI and describes the capacity of systems to learn from problem-specific training data to automate the process of analytical model building and perform cognitive tasks. It automatically learns predictive patterns from huge data sets. Deep learning is a machine learning concept based on artificial neural networks. For many applications, deep learning models outperform machine learning models. Deep learning is particularly useful in domains with large and high-dimensional data (Janiesch et al., 2021). It can recognize patterns in data that are too complex for traditional machine learning algorithms.

Machine learning and deep learning enable predictive and even prescriptive quality management. There are several studies demonstrating the feasibility of machine learning or deep learning for the prediction of products quality based on the process data, which enables to support of quality control e.g. (Ke & Huang, 2020; Msakni et al., 2023; Tercan & Meisen, 2022; Zhang & Lei, 2017). Early process deviations can be detected and preventive measures can be taken. The application of deep learning in combination with machine vision enables a higher degree of automated visual inspection. DL model is trained on the given data, where neural networks discover the underlying patterns in classes of images and automatically works out the most descriptive and salient features. In traditional machine vision, it is necessary to choose which features are important (manual extraction) in each given image (Mahony et al., 2019). Machine learning and deep learning plays important role in product design, and can learn automatically from the performance of previous product generations and end-to-end data. Machine learning and deep learning improve the efficiency of digital twins by providing insights that go beyond what real-world sensors provide. Using machine learning and deep learning to evaluate the performance of the new product designs allows rate them more quickly than is required for conventional computational flow dynamics analysis.

Other examples of AI applications include root cause analysis, understanding of customer needs and forecast of market trends, optimization of production volume and resource allocation, predictive maintenance, route planning in internal logistics and transportation (Lo et al., 2021), etc.

Blockchain

Blockchain is a decentralized database technology that provides a mechanism for immutability guarantee and the absence of a central entity for decision-making in data operations. Blockchain is a form of distributed ledger technology to enhance traceability (Tsang et al., 2019). Supply chains have become increasingly complex, making it difficult to ensure transparency throughout the whole supply chain. Several studies confirm the importance of the use of blockchain technology within supply chain management, while the main objective is transparency and data quality. It solves the issues of distrust based on unchanged information and traceable records through standardized norms and agreements. According to Liu & Shen adopting blockchain can encourage the supply chain to provide high-quality products (Liu & Shen, 2020).

The emergence of new technological tools doesn't replace traditional quality management tools, their purpose remains relevant. According to Santos et al. Q4.0 combines new technologies with common quality methods and tools, to achieve new optimums in performance, operational excellence, and also, in innovation (G. Santos et al., 2021). For example, the paper-based checklist, which is used for collecting data that could then be analysed is now moving to the next level, when scanners gather information and enter it straight into databases and laser-based and optical measuring devices automatically check parts and store data. Data can be analysed with AI to seek out patterns that where is the greatest concentration of failures. In the case of the traditional Ishikawa diagram, problem-solving team members gather ideas via brainstorming for the Ishikawa diagram, however, insights from BD analysis can be used to define them and categorize and the Pareto diagram can be created automatically. SPC is moving from merely statistical control to real time diagnosis with minimum human intervention.

3.4. Quality 4.0 Maturity Models

On the base of the review of literature and internet sources, it is possible to state that only a few Q4.0 MM have been published so far. The majority of studies are oriented to Industry 4.0 MM, which were described in the subchapter 1.3. I4.0 MM consists of dimensions or areas that are mostly also relevant to the field of quality management and can help to understand some of the Q4.0 areas and in deriving Quality 4.0 elements.

Quality 4.0 models that have been published define the main areas of Quality 4.0 – so called dimensions forming the model and related elements characterizing individual dimensions. The number of dimensions varies from model to model. In the case of Quality 4.0 MM the dimensions and elements are assessed by the relevant assessment scale enabling identification of the Q4.0 maturity level.

(1) Quality 4.0 Model Developed by LSN Research

The most frequently cited Q4.0 framework is the model developed by the LSN Research company, which consists of 11 dimensions. It can be used by organizations to interpret their current state and identify what changes are needed to move to the future state. The dimensions forming the framework are categorized into three categories - people, technology and processes as follows (Jacob, 2017; Murugesan, 2022):

People

(1) *Culture* (process participation, responsibility, credibility, cross-functional empowerment),

(2) *Leadership* (clear quality goals and KPI, cross-functional ownership),

(3) *Competency* (expertise, experiences, appraisal, individual),

Processes

(4) *Management Systems* (robotic process automation, connected processes, autonomous processes, autonomous system),

(5) *Compliance* (automated compliance, analytics to alert breaches, blockchain providing automated audit-ability),

(6) *Scalability* (Cloud Computing, Infrastructure as a Service),

Technology

(7) *Data* (BD leverage),

(8) *Analysis* (prescriptive analytics with the use BD analytics, machine learning and artificial intelligence),

(9) *Connectivity* (connection between business information technology (IT) and operational technology (OT), connected people, devices, products),

(10) *Collaboration* (cross-functional and global; social media, blockchain),

(11) *Applications development* (apps usage, advanced apps utilizing virtual and augmented reality).

The above-mentioned dimensions were applied in several studies, e.g. (Alzahrani et al., 2021; Armani et al., 2021; Zulqarnain et al., 2022). The work presented by (Zulqarnain et al., 2022) using the LSN's Q4.0 dimensions focuses on the adjustment of dimensions categorization according to the ISO 9001 quality management system model and elements of the individual dimensions are modified by the authors.

(2) Quality 4.0 Maturity Assessment Models

Quality 4.0 Maturity Assessment Model published by Mtotywa consists of 7 dimensions and 28 related elements (Mtotywa, 2022):

(1) *Management commitment to technology and innovation* (Leadership for Q4.0, Investments in smart technologies, Enabling culture of creativity and innovation, Leading Gemba activities for Q4.0),

(2) *Customer focus* (Customer Satisfaction, Customized customer, Customer relationship management, Penalty-reward contrast analysis),

(3) *Employee involvement and empowerment* (Training and retraining, Technical skills, Communication, Implemented Q4.0 culture),

(4) *Process and systems integration and management* (Simulation of process design and improvement, AI for quality inspection and analysis, Real time process performance enabled by BD, Capabilities for instant reconfiguration of processes),

(5) *Knowledge for decision making and future production* (Access to information, Access to information analytics, Availability for early decision-making, Early failure prediction),

(6) *Root cause analysis and sustainable solution* (Problem identification technologies, Statistical root cause analysis, Design of experiment, Process capability assessment),

(7) *Operational environment benchmarking* (Technology in use, Industry performance benchmark, Customer demand changes, Business sustainability benchmark).

For the assessment of the elements related to the individual dimensions 5 level scales are used and on the base of the results from the calculation of each dimension overall Q4.0 Maturity Index is determined. The model can be used to identify the current state of Q4.0 maturity level of organizations and help to identify weaknesses that require focus and enable to define the actions that needs to be taken for further development and improvement towards higher level of maturity.

Another Quality 4.0 Maturity Assessment Model published by Nenadál et al. defines 4 main Q4.0 dimensions with 22 elements (Nenadál et al., 2022):

(1) *Strategic Direction* (Vision towards Q4.0, Context of organization, Technological development, Quality management principles),

(2) *People and Culture* (Leadership, Organization culture, Organization knowledge, Corporate Sustainability, Innovation capacity and Support),

(3) *Processes* (Process management, Process performance management, Process infrastructure and IT support, Process improvement),

(4) *Methods and Tools* (BD, Smart sensors, E-value chain, Cloud Computing, Feedback loops, IS security, Internet of Things, Self-assessment, Advanced quality management tools).

In order to perform maturity assessment there are special assessment matrices in which all items are described by generic descriptors. Maturity is defined within seven Q4.0 maturity levels.

(3) Comparison of the Quality 4.0 Models

The dimensions of the previous models are categorized in the Table 1 into 3 categories – People, Processes, Technology.

Table 1. Dimensions of Quality 4.0 Models

Areas	**(Murugesan, 2022)**	**(Mtotywa, 2022)**	**(Nenadál et al., 2022)**
People	Culture; Leadership; Competency	Management commitment to technology and innovation; Employee involvement and empowerment	Strategic direction; People and culture
Process	Management Systems, Compliance; Scalability	Process and systems integration and management;	Processes
Technology	Data; Analysis; Connectivity; Collaboration; Applications development	Knowledge for decision making and future production; Root cause analysis and sustainable solution; Customer focus; Operational environment benchmarking	Methods and tools

Source: own elaboration.

As can be seen in the table, the area of People is covered by all the models. The dimensions in this category in the cases of all models involve elements like Culture and Leadership supporting Q4.0, Competencies of employees and their empowerment. Nenedál, et al. within the cultural issues involved the sustainability aspect, which is related to Q4.0.

The Process area is described by the elements in general from the connection of processes towards autonomous processes and system. The Q4.0 maturity models' elements related to the process dimensions involves real-time process performance, digitalization of process design and improvement, flexible process reconfiguration and management. Model of the LSN Research separately involves dimensions related to the compliance process.

The field of technology in the models is reflected by the elements like BD, Advanced analytics, Technologies enabling connectivity within organization functions and value chain (e.g., IoT, CC, integration of IT and OT), and Applications and tools. (Mtotywa, 2022) separately involved dimension for technologies used for Root cause analysis and dimensions like Customer focus and Benchmarking, where the basis are the previously mentioned technologies that are used for these fields.

3.5. Quality Management System 4.0 Building

ISO 9001:2015 QMS standard provides a framework for ensuring quality processes are in place and continuous improvement is running. It helps organizations to enhance customer satisfaction through effective application of system and processes assuring conformity and improvement (ISO 9001, 2015). Quality 4.0 principles and tools can be integrated with the QMS to create a powerful tool for achieving quality excellence. The integrated approach leading to QMS 4.0 can yield significant benefits for organizations seeking to optimize their processes, enhance efficiency, and maintain a competitive edge in today's fast-paced business landscape.

Achieving quality excellence requires a leadership commitment. Without a clear digital strategy supporting digital transformation throughout the organization, the QMS 4.0 implementation cannot be effectively and holistically realized. Many organizations apply within quality management partial digital solutions and tools, but a holistic approach is missing often due to the lack of top management support and missing or unclear digital strategy. The implementation of QMS4.0 must contribute to the organization's overall digital strategy and also the digital strategy must support the QMS development towards QMS 4.0. The building of QMS 4.0 consists of the following steps:

- Evaluation of the current state of QMS regarding Q4.0 principles and tools and identification of gaps.
- Goal setting and creation of roadmap for integrating Quality 4.0 principles and tools into existing QMS, the definition of timelines, and allocation of resources (including suitable software solution) to ensure a smooth transition towards QMS 4.0.
- Employee training to ensure necessary skills and knowledge.
- Implementation, monitoring and evaluation of QMS transformation. Regular revision of QMS 4.0 on the base of results and evolving needs of customers and other stakeholders.

According to Graham Quality 4.0 is not an 'off the shelf' product that can be bolted onto a QMS, rather it is a phase through which quality management is progressing and a means by which organisations can re-examine what they do and how they do it (Graham, 2022).

3.6. EFQM Model and Industry 4.0 Relationship

The EFQM Model is a globally recognised framework that supports organisations in managing change and improving performance. Since it was launched in 1992, it has been revised several times and the latest version was released in 2020. Central to the rationale of the EFQM Model 2020 is the connection between the Purpose and Strategy of an organisation and how that is used to help Create Sustainable Value for its most important stakeholders and deliver outstanding Results (EFQM, 2020). The EFQM 2020 model emphasizes transformation and future focus. The sub-criterion *5.2 Transformation for the Future* (within criterion *5 Driving Performance & Transformation* in the Execution phase) explicitly mentions it (Nenadál, 2020). However, in the work of (Fonseca et al., 2021) it is pointed out that in the Direction phase within the criteria *1 Direction* and *2 Organisational Culture & Leadership* the transformation and technology are not explicitly mentioned.

The EFQM 2020 model mindset is framed by creativity, innovation, and disruptive thinking, which are essential for Industry 4.0. EFQM criteria and RADAR, organizational self-assessments, or external assessments can challenge, support, and shape organizations to move towards new knowledge and performance. (Fonseca et al., 2021) focused on the identification of the EFQM Model links with Industry 4.0 on the base of the model criteria and guidance points. The relations between the EFQM model and Industry 4.0 are shown in Table 2.

Table 2. Selected EFQM Model Criteria and Sub-Criteria and Their Link to Industry 4.0

Selected Criteria and Sub-Criteria of the EFQM Model	EFQM 2020 Model Guidance Points Related to I4.0
1.3 Understand the Ecosystem, Own Capabilities & Major Challenges	Understands the ecosystem, including megatrend implications. Evaluates the data, information gathered from across its ecosystem to understand the major challenges.
2.2 Create the Conditions for Realising Change	Facilitates an open mindset towards learning in the pursuit of its strategy, encouraging the improvement and transformation of the organization.
2.3 Enable Creativity and Innovation	Understands the importance of focusing on creativity, innovation, and disruptive thinking in achieving organization's strategy. Engages learning and collaboration networks to identify opportunities for creativity and innovation.
5.2 Transform the Organisation for the Future	Identifies the transformation and change needs. Adapts current strategy and existing business models to meet future needs. Restructures its value creation in a timely manner and other

	organizational processes based on operational excellence and future needs.
5.3 Drive Innovation & Utilise Technology	Provides the capabilities, resources, and tools that develop and sustain creativity and innovation. Exploits the potential that new technologies have to support value creation, improvements to its infrastructure, and adaptability of its processes. Introduces relevant developments in technology.
5.4 Leverage Data, Information & Knowledge	Ensures that it has identified the proper data and acquires them to support its transformation plans and manage the products and services. Uses advanced analytics, including predictive models, to extract value from data and support decisions. Converts data into information and for creating sustainable value. Makes use of the knowledge held by key stakeholders to generate ideas and innovations.
5.5 Manage Assets & Resources	Identifies and responsibly manages the critical assets and resources that are vital for its strategy, performance, and transformation needs.
6. Stakeholder Perceptions	Customer perception results: e.g. the usage of technology by the organization to deliver sustainable value. People's perception results: e.g. the co-existence of people and robots, the use of AI and augmented reality. Business and governing stakeholders' results: e.g. the ability of the organization to scan the horizon, spot megatrends, and deal with them successfully. Partners and suppliers' perception results: e.g. the rate of implementation of new technologies and changes.
7. Strategic & Operational Performance	Achievement of strategic objectives, Achievements in driving performance, Achievements in driving transformation, Predictive measures for the future.

Source: (Fonseca et al., 2021).

The EFQM Model may support the successful digital transformation of organizations and provide an integrated strategic framework for quality, excellence, and sustainability, within the I4.0 paradigm.

Chapter 4. Competencies for Quality 4.0

4.1. Definition of Competency

According to ISO 9001 competency is defined as an "ability to apply knowledge and skills to achieve intended results" (ISO 9001, 2015). Several research sources state that competence is a combination of knowledge, skills and attitudes. Skills are often divided into hard and soft. *Hard skills* relate to the technical aspect of tasks performed within a job position and frequently take into account of the acquisition of knowledge. *Soft skills* are intra and inter-personal skills, essential for personal development, social participation and workplace success (Hendarman & Cantner, 2018). In the work of Belkadi et al. competencies are defined as a set of characteristics or dispositions that can be cognitive, affective, behavioural and motivational which enable a person to perform well in a specific situation (Belkadi et al., 2006). Competency is a set of resources that a person acquires or needs to acquire, in order to perform an activity inside a certain context with a specific performance level (El Asame & Wakrim, 2018). According to Hecklau et al. competencies can be categorized as (Hecklau et al., 2016):

- *technical competencies* – they are made up of a set of knowledge and skills for the workplace position,
- *methodical* – they are made up of skills and abilities for solving problems and decision-making,
- *social* – they are necessary for effective communication and building positive relationships with others,
- *personal* – they are formed by individual values, motives and attitudes.

Compared with the ISO 9000 definition of competence, several sources except the knowledge and skills involve personal aspects (values, attitudes, aspirations, etc.) as a component of the competence.

4.2. Competencies of the Digital Era

Digitalization transforms how human beings communicate, produce things, transport people and goods, and interact. As technological breakthroughs rapidly shift the frontier between the work tasks performed by humans and those performed by machines and algorithms, global labour markets are changing. Many studies confirmed that lack of competencies is one of the main barriers to I4.0 implementation in organizations. People are crucial for the success of digital transformation. The new technologies drive business growth, job creation and demand for specialists but their deployment also result in the automation of certain tasks and the disappearance of entire job positions. New technologies bring new job positions. Competencies required to perform most of the jobs are shifting significantly. Simple and monotonous processes are being automated, while other processes become more complex. New required competencies are connected with higher responsibility and empowerment. Employees must be able to take on more strategic, coordinated and creative tasks. The competency set for Human Capital 4.0 brings together five main existing competencies shown in Figure 5.

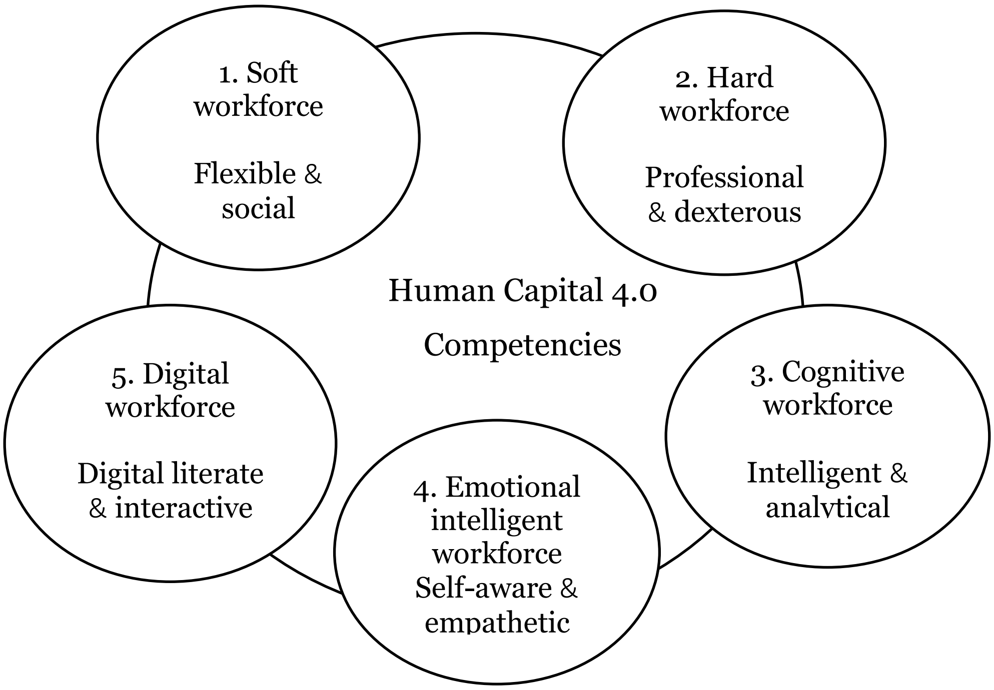

Figure 5. Competency Set for Human Capital 4.0
Source: (Flores et al., 2020).

The competency set involves (Flores et al., 2020):

- Soft workforce – these competencies will enable the interconnectivity, self-adaptability and decentralisation of job positions sought by Industry 4.0 at the human capital level. These skills are communication, teamwork or cooperation, leadership, willingness to learn, self-development, negotiation and flexibility or adaptability.
- Hard workforce – competencies to be able to cope with industrial processes, standards understanding, problem-solving techniques, designing with software, human-machine interactions, digital network settings, digital security and coding or programming.

- Cognitive workforce – skills of the cognitive workforce, who is intelligent and analytical are verbal, numerical and spatial (coordination, memory, decision-making, problem-solving thinking, abstract reasoning, analytical thinking).
- Emotional intelligent workforce – competencies like self-awareness, self-control, positive outlook, empathy, achievement orientation and motivation.
- Digital workforce – programming, cybersecurity, digital networks, cloud computing, databases, web development and also the management of Industry 4.0 technologies (e.g. IoT, BD analytics, 3D printing, simulation, AR and VR).

According to the study of the World Economic Forum (WEF), where employers were surveyed among the 10 leading competencies of 2022 analytical thinking and innovation, creativity and originality (methodical competencies) and active learning (personal competence) are listed as the top three competencies. Technology design and programming highlight in the list the growing demand for various forms of technical competencies. Other methodical competencies like critical thinking and analysis and complex problem solving are following and from the social competencies leadership and emotional intelligence are within the list. Competencies demand trends reflect continued fall in demand for manual skills and physical abilities and decrease in demand for skills related to the management of financial and other resources, as well as, basic technology installation and maintenance skills.

In the ranking of top ten competencies of 2025 critical thinking and complex problem-solving top the list of competencies that employers believe will grow in prominence in the next 5 years. Newly emerging personal competence are resilience, stress tolerance and flexibility. Technology use, monitoring and control reflect the need for further development of technological competencies. The top competencies for 2022 and 2025 according to WEF are in the Table 3 (World Economic Forum, 2018, 2020).

Table 3. Top 10 Competencies of 2022 and 2025

Top 10 competencies of 2022	**Top 10 competencies of 2025**
Analytical thinking and innovation	Analytical thinking and innovation
Active learning and learning strategies	Active learning and learning strategies
Creativity, originality and initiative	Complex problem-solving
Technology design, programming	Critical thinking and analysis
Critical thinking and analysis	Creativity, originality and initiative
Complex problem-solving	Leadership and social influence
Leadership and social influence	Technology use, monitoring and control
Emotional intelligence	Technology design, programming
Reasoning problem-solving and ideation	Resilience, stress tolerance and flexibility
System analysis and evaluation	Reasoning, problem solving and ideation

Source: (World Economic Forum, 2018, 2020).

In the study of Hecklau et al., Industry 4.0 challenges were defined (economic, social, technical, environmental, political and legal challenges) and related Industry 4.0 competencies were derived and classified as follows (Hecklau et al., 2016):

- Technical: State of art knowledge, Technical skills, Process understanding; Media skills, Coding skills, Understanding IT security
- Methodological: Creativity, Entrepreneurial thinking, Problem solving, Decision making, Analytical skills, Research skills, Efficiency orientation
- Social: Intercultural skills, Language skills, Communication; Networking; Teamwork and cooperation; Knowledge transfer, Leadership
- Personal: Flexibility, Ambiguity tolerance, Motivation to learn, Ability to work under pressure, Sustainability mindset, Compliance

All the top 10 leading competencies from the WEF study are included in the above-mentioned categorization except emotional intelligence and system analysis and evaluation, which are important as horizontal and vertical integration increases cross-functional cooperation as well as cooperation through the organization border and emotional intelligence is important in inter-personal collaboration. System analysis and evaluation relate to the connection and integration aspect of Industry 4.0.

The above-mentioned categorization includes the technical competencies in comparing to the WEF top ten skills media skills and understanding IT security. The social competencies involve intercultural and language skills as the connection and integration of all partners from various countries is increasing. Also, the ability to transfer knowledge is important to support the Industry 4.0 culture.

4.3. Competencies of Quality 4.0 Professionals

Implementation of the Q4.0 brings challenges in connection with the new required competencies of quality professionals. Competence planning should be an important part within the project of I4.0 and Q4.0 implementation. For Q4.0, a range of new knowledge and skills are required for quality professionals and training will play a major role. The changes and challenges that quality professionals need to face are:

- real time data gathering and monitoring (processes, devices, products, customers),
- advanced analytical tools for BD analysis and applications (descriptive – generation of information; diagnostic – pattern recognition; predictive – forecast; prescriptive analytics – decision making),

- real time picture for decision making,
- automation of tasks,
- VR and AR interfaces and human–machine interactions,
- new technologies and smart media,
- scalable software solutions for quality management,
- cross-functional collaboration and collaboration,
- connected supply chain and networking,
- understanding customer needs to the next level,
- new leadership challenges.

Quality professionals need to learn computer science skills and data mining techniques to thrive within I4.0. Quality professionals may need the right tools to know how to interpret large volumes of machine data effectively, beyond the current statistical knowledge applications.

In the study of Escobar et al. there were three different levels of competencies for Q4.0 proposed within the certification curricula for Green, Black and Master Black Belt, which are oriented to hard skills and related knowledge (Escobar et al., 2021). The followings were proposed:

- Big Data – understanding of the 10 Vs, creating features, pre-processing techniques; in the case of Black and Master Black Belt also understand the learning curves to guide the generation of data either to generate more data, or more features, or both.
- Machine learning theory – understanding of model validation, and feature selection methods, bias variance off, and generalization evaluation metrics – for all three levels.
- Machine learning algorithms – understanding and ability to train nine machine learning algorithms; in the case of Black and Master Black Belt ability to optimize prediction through a decision combination scheme.
- Programming – the ability to write the basic code to run the machine learning analyses, in the case of Black and Master Black Belt levels - ability to write the deployment code, learning, re-learning. ability to identify the driving features of the system to guide process redesign/optimization.
- Problem strategy – ability to successfully apply steps of the problem-solving strategy.

The work of Santos et al. dealing with the competencies of Quality Managers 4.0 is based on the top ten competencies published by WEF (presented in the previous sub-chapter). The set of competencies, which were investigated in the case of Quality Managers 4.0 and considered relevant involves: critical thinking; creativity; leadership; emotional intelligence; decision making; negotiation; customer orientation; communication; teamwork; focus on results; conflict management; ethics; assertiveness; commitment; motivation; flexibility; openness to change (G. Santos et al., 2021).

On the base of the literature sources competencies relevant to Q4.0 Professionals are summarized in Table 4.

Table 4. Competencies Relevant for Quality 4.0 Professionals

Competence category	Competence
Technical	Smart technology and media use, Big data and data mining knowledge and skills, Machine learning knowledge and skills, Programming skills, IT security knowledge
Methodical	Creativity, Customer orientation, Complex problem solving, Critical thinking, Analytical skills, Decision making, Efficiency orientation
Social	Intercultural skills, Cross-functional cooperation, Networking, Communication, Knowledge transfer, Leadership and social influence
Personal	Flexibility, Openness to change, Active learning, Emotional intelligence, Stress tolerance; Sustainability mindset, Compliance

Source: own elaboration

The competencies will vary as well as their level based on the positions – Quality Manager, Quality Engineer, Quality Auditor, Six Sigma Specialist (Green, Black, Master Black Belt).

Conclusions

Since 2011, when Industry 4.0 as a term was used firstly, many definitions were developed by academics, practitioners, government, and private organizations that differ in their primary focus on Industry 4.0 aspects and principles. Several frameworks have been developed that enable to identify the current state of I4.0 readiness or maturity and create a roadmap for further development and achievement of improvements needed in terms of the digital strategy of organization. The models differ in their components and assessment instruments.

Since 2015, European Union has been supporting digital transformation through various initiatives. Many member states as well as Poland, Czech Republic and Slovakia have developed their own I4.0 strategies and implemented various activities towards I4.0. All the countries established EDIHs and DIHs. In the latest DESI Index, the countries achieved a score below the EU average but in a more specific study - Readiness for the Future of Production conducted by the World Economic Forum Poland and the Czech Republic were classified as leading countries. Government support of digitalization of industry is important to support industry competitiveness of a country but supporting activities must be realized also on the level of organizations, where top management plays a crucial role.

Quality 4.0 as a naturally emerging concept in the era of Industry 4.0 that has attracted attention of many quality experts, who have tried to define it, specify main principles, characteristics and tools. Currently, only few Quality 4.0 maturity models exist. Quality 4.0 is becoming more important to all organisations in supporting existing QMS as digitalization progresses. Development towards QMS 4.0 integrating the Quality 4.0 concept with the QMS model according to ISO 9001 requires a systematic approach and mainly support of top management and clear digital strategy on the level of organization. The latest version of the EFQM model supporting organisations in managing change and improving performance may support the successful digital transformation of organizations and provide an integrated strategic framework for quality, excellence, and sustainability, within the I4.0 paradigm.

Digitalization forms a set of new core competencies. Quality 4.0 challenges the work of quality professionals and require new hard and soft competencies to be developed in quality professionals that will vary and also their level will be different depending on the type of position – Quality Manager, Quality Engineer, Quality Auditor, Six Sigma Specialist (Green, Black, Master Black Belt).

References

Alzahrani, B., Bahaitham, H., Andejany, M., & Elshennawy, A. (2021). How Ready Is Higher Education for Quality 4.0 Transformation according to the LNS Research Framework? *Sustainability*, *13*(9), 5169. https://doi.org/10.3390/su13095169

Antony, J., Bhat, S., Jayaraman, R., McDermott, O., Sony, M., & Snee, R. (2022). The genealogy of Quality 4.0: From inspection to automation, the quest to meet standards evolves. *ISE Magazine*.

Armani, C. G., De Oliveira, K. F., Munhoz, I. P., & Akkari, A. C. S. (2021). Proposal and application of a framework to measure the degree of maturity in Quality 4.0: A multiple case study. *Advances in Mathematics for Industry 4.0* (s. 131–163). Elsevier. https://doi.org/10.1016/B978-0-12-818906-1.00006-1

ASQ. (2020). *Quality 4.0*. ASQ. https://asq.org/quality-resources/quality-4-0

Belkadi, F., Bonjour, E., & Dulmet, M. (2006). A Fuzzy Approach for Competency Characterisation Based on a Work Situation Analysis. *IFAC Proceedings Volumes*, *39*(4), 200–205. https://doi.org/10.3182/20060522-3-FR-2904.00032

Benotsmane, R., Kovács, G., & Dudás, L. (2019). Economic, Social Impacts and Operation of Smart Factories in Industry 4.0 Focusing on Simulation and Artificial Intelligence of Collaborating Robots. *Social Sciences*, *8*(5), 143. https://doi.org/10.3390/socsci8050143

Castagnoli, R., Büchi, G., Coeurderoy, R., & Cugno, M. (2022). Evolution of industry 4.0 and international business: A systematic literature review and a research agenda. *European Management Journal*, *40*(4), 572–589. https://doi.org/10.1016/j.emj.2021.09.002

Confederation of Industry of the Czech Republic. (2023). https://www.spcr.cz/prumysl-4-0

De Carolis, A., Macchi, M., Negri, E., & Terzi, S. (2017). A Maturity Model for Assessing the Digital Readiness of Manufacturing Companies. V H. Lödding, R. Riedel, K.-D. Thoben, G. Von Cieminski, & D. Kiritsis (Ed.), *Advances in Production Management Systems. The Path to Intelligent, Collaborative and Sustainable Manufacturing* (Vol. 513, s. 13–20). Springer International Publishing. https://doi.org/10.1007/978-3-319-66923-6_2

Deloitte. (2015). *Industry 4.0: Challenges and solutions for the digital transformation and use of exponetial technologies*. Deloitte.

Deloitte. (2018). *Digital Maturity Model*. https://www2.deloitte.com/content/dam/Deloitte/global/Documents/Technology-Media-Telecommunications/deloitte-digital-maturity-model.pdf

Drath, R., & Horch, A. (2014). Industrie 4.0: Hit or Hype? [Industry Forum]. *IEEE Industrial Electronics Magazine*, *8*(2), 56–58. https://doi.org/10.1109/MIE.2014.2312079

EFQM. (2020). *The EFQM Model*.

El Asame, M., & Wakrim, M. (2018). Towards a competency model: A review of the literature and the competency standards. *Education and Information Technologies*, *23*(1), 225–236. https://doi.org/10.1007/s10639-017-9596-z

Escobar, C. A., Chakraborty, D., McGovern, M., Macias, D., & Morales-Menendez, R. (2021). Quality 4.0—Green, Black and Master Black Belt Curricula. *Procedia Manufacturing*, *53*, 748–759. https://doi.org/10.1016/j.promfg.2021.06.085

Etonam, A. K., Gravio, G. D. (2019). Augmented Reality (AR) Application in Manufacturing Encompassing Quality Control and Maintenance. *International Journal of Engineering and Advanced Technology*, *9*(1), 197–204. https://doi.org/10.35940/ijeat.A1120.109119

European Commission. (2016). *Digitising European Industry: Reaping the full benefits of a Digital Single Market*.
European Commission. (2018a). *Digital Transformation Monitor—Slovakia: Smart Industry*. European Commission.
European Commission. (2018b). *Shaping Europe's digital future*. https://digital-strategy.ec.europa.eu/en/library/digitising-european-industry-initiative-nutshell
European Commission. (2022). *Digital Economy and Society Index (DESI) 2022*. https://digital-strategy.ec.europa.eu/en/library/digital-economy-and-society-index-desi-2022
European Commission. (2020). *Smart Specialisation Platform*. https://s3platform.jrc.ec.europa.eu/digital-innovation-hubs-tool
European Court of Auditors. (2020). *Digitising European Industry: An ambitious initiative whose success depends on the continued commitment of the EU, governments and businesses* [Special Report].
Flores, E., Xu, X., & Lu, Y. (2020). Human Capital 4.0: A workforce competence typology for Industry 4.0. *Journal of Manufacturing Technology Management*, *31*(4), 687–703. https://doi.org/10.1108/JMTM-08-2019-0309
Fonseca, L., Amaral, A., & Oliveira, J. (2021). Quality 4.0: The EFQM 2020 Model and Industry 4.0 Relationships and Implications. *Sustainability*, *13*(6), 3107. https://doi.org/10.3390/su13063107
Frank, A. G., Mendes, G. H. S., Ayala, N. F., & Ghezzi, A. (2019). Servitization and Industry 4.0 convergence in the digital transformation of product firms: A business model innovation perspective. *Technological Forecasting and Social Change*, *141*, 341–351. https://doi.org/10.1016/j.techfore.2019.01.014
Gabriel, M., & Pessl, E. (2016). Idustry 4.0 and Sustainability Impacts: Critical Discussion of Sustainability Aspects with a Special Focus on Future of Work and Ecological Consequences. *ANNALS of Faculty Engineering Hunedoara – International Journal of Engineering*, *14*(2), 131–137.
Government of Czech Republic. (2017). *Action plan on the future of the automotive industry in the Czech Republic*. https://www.vlada.cz/assets/media-centrum/aktualne/Akcni-plan-o-budoucnosti-automobiloveho-prumyslu-v-CR.pdf
Government Office of the Czech Republic. (2017). *Action Plan fir Society 4.0*. https://www.dataplan.info/img_upload/7bdb1584e3b8a53d337518d988763f8d/1_2-ap-spolecnost-4_0.pdf
Graham, M. (2022). *ISO 9001:2015 and Quality 4.0*. NQA.
Hecklau, F., Galeitzke, M., Flachs, S., & Kohl, H. (2016). Holistic Approach for Human Resource Management in Industry 4.0. *Procedia CIRP*, *54*, 1–6. https://doi.org/10.1016/j.procir.2016.05.102
Hendarman, A. F., & Cantner, U. (2018). Soft skills, hard skills, and individual innovativeness. *Eurasian Business Review*, *8*(2), 139–169. https://doi.org/10.1007/s40821-017-0076-6
Ibarra, D., Ganzarain, J., & Igartua, J. I. (2018). Business model innovation through Industry 4.0: A review. *Procedia Manufacturing*, *22*, 4–10. https://doi.org/10.1016/j.promfg.2018.03.002
IFR. (2018). *Robot density rises globally*. https://ifr.org/ifr-press-releases/news/robot-density-rises-globally
Impuls. (2015). *Industry 4.0 Readiness Online Self-Check for Businesses*. https://www.industrie40-readiness.de/?lang=en
ISO 9001. (2015). *ISO 9000:2015 Quality management systems: Fundamentals and vocabulary*. ISO.

Jacob, D. (2017, 7). What is Quality 4.0? [LSN]. *Latest Insights from Our Analysts*. https://blog.lnsresearch.com/quality40
Janiesch, C., Zschech, P., & Heinrich, K. (2021). Machine learning and deep learning. *Electronic Markets*, *31*(3), 685–695. https://doi.org/10.1007/s12525-021-00475-2
Javaid, M., Haleem, A., Pratap Singh, R., & Suman, R. (2021). Significance of Quality 4.0 towards comprehensive enhancement in manufacturing sector. *Sensors International*, *2*, 100109. https://doi.org/10.1016/j.sintl.2021.100109
Kagermann, H., Wahlster, W., & Helbig, J. (2013). *Recommendations for implementing the strategic initiative INDUSTRIE 4.0. Final report of the Industrie 4.0 Working Group*. Forschungsunion, Acatech.
Ke, K.-C., & Huang, M.-S. (2020). Quality Prediction for Injection Molding by Using a Multilayer Perceptron Neural Network. *Polymers*, *12*(8), 1812. https://doi.org/10.3390/polym12081812
Klötzer, C., & Pflaum, A. (2017). *Toward the Development of a Maturity Model for Digitalization within the Manufacturing Industrys Supply Chain*. Hawaii International Conference on System Sciences. https://doi.org/10.24251/HICSS.2017.509
Kupper, D., Knizek, C., Reyson, D., & Noecker, J. (2019). *Quality 4.0 Takes More Than Technology*. https://www.bcg.com/publications/2019/quality-4.0-takes-more-than-technology
Liu, Y., & Shen, B. (2020). Quality Management and Blockchain Adoption in a Supply Chain. *IFAC-PapersOnLine*, *53*(2), 10732–10736. https://doi.org/10.1016/j.ifacol.2020.12.2853
Lo, C. K., Chen, C. H., & Zhong, R. Y. (2021). A review of digital twin in product design and development. *Advanced Engineering Informatics*, *48*, 101297. https://doi.org/10.1016/j.aei.2021.101297
Mahony, N. O., Campbell, S., Carvalho, A., Harapanahalli, S., Velasco-Hernandez, G., Krpalkova, L., Riordan, D., & Walsh, J. (2019). *Deep Learning vs. Traditional Computer Vision*. https://doi.org/10.48550/ARXIV.1910.13796
McKinsey & Company. (2015). *Industry 4.0: How to navigate digitization of the manufacturing sector*. https://www.mckinsey.com/~/media/McKinsey/Business%20Functions/Operations/Our%20Insights/Industry%2040%20How%20to%20navigate%20digitization%20of%20the%20manufacturing%20sector/Industry-40-How-to-navigate-digitization-of-the-manufacturing-sector.ashx
Meloeny, S. (2022). What is Industry 4.0. *Calsoft*. https://www.calsoft.com/what-is-industry-4-0/
Ministry of Development Funds and Regional Policy. (2021a). *European Funds for Digital Development*. European Funds for Digital Development. https://www.rozwojcyfrowy.gov.pl/
Ministry of Development Funds and Regional Policy. (2021b). *The European Funds for Modern Economy*. The European Funds for Modern Economy.
Ministry of Development Funds and Regional Policy. (2023). *Digital Poland Program*. Service of Digital Poland Program. https://www.polskacyfrowa.gov.pl/strony/o-programie/
Ministry of Economic Development and Technology. (2019). *What we do?* The Future Industry Platform. https://przemyslprzyszlosci.gov.pl/co-robimy/
Ministry of Economy of the Slovak Republic. (2016). *Concept of Smart Industry for Slovakia*. Ministry of Economy of the Slovak Republic. https://www.mhsr.sk/inovacie/strategie-a-politiky/smart-industry?csrt=17427625980955665413

Ministry of Economy of the Slovak Republic. (2019). *Smart Industry Action Plan for Slovakia*. Ministry of Economy of the Slovak Republic. https://www.mhsr.sk/inovacie/strategie-a-politiky/akcny-plan-inteligentneho-priemyslu-sr?csrt=5818330575582463883
Ministry of Finance of the Slovak Republic. (2021). *Recovery and Resilience Plan*. https://www.mfsr.sk/sk/verejnost/plan-obnovy-odolnosti/
Ministry of Industry and Trade of Czech Republic. (2015). *National Initiative: Industry 4.0*. https://storage.googleapis.com/businessinfo_cz/files/dokumenty/narodni-iniciativa-prumysl-40.pdf
Ministry of Industry and Trade of Czech Republic. (2016a). *Industry 4.0 Initiative*. https://www.mpo.cz/assets/dokumenty/53723/64358/658713/priloha001.pdf
Ministry of Industry and Trade of Czech Republic. (2016b). *Industry Cluster 4.0*. https://ic40.cz/
Ministry of Investments Regional Development and Informatization of the Slovak Republic. (2021). *Strategy and action plan for improving Slovakia's position in the DESI index until 2025*. https://www.mirri.gov.sk/sekcie/informatizacia/digitalna-transformacia/strategia-a-akcny-plan-na-zlepsenie-postavenia-slovenska-v-indexe-desi-do-roku-2025/index.html
Ministry of Investments, Regional Development and Informatization of the Slovak Republic. (2022). *Action Plan of Digital Transformation of Slovakia 2023-2026*. https://www.mirri.gov.sk/sekcie/informatizacia/digitalna-transformacia/akcny-plan-digitalnej-transformacie-slovenska-na-roky-2023-2026/index.html
Ministry of Investments, Regional Development and Informatization of the Slovak Republic. (2019b). *Action Plan of Digital Transformation of Slovakia 2019-2022*. https://www.mirri.gov.sk/sekcie/informatizacia/digitalna-transformacia/akcny-plan-digitalnej-transformacie-slovenska-na-roky-2019-2022/index.html
Ministry of Investments, Regional Development and Informatization of the Slovak Republic. (2019a). *Strategy of Digital Transformation of Slovakia 2030*. https://www.mirri.gov.sk/sekcie/informatizacia/digitalna-transformacia/strategia-digitalnej-transformacie-slovenska-2030/
Ministry of Labour and Social Affairs of the Czech Republic. (2016). *Work 4.0*. https://www.mpsv.cz/web/cz/prace-4.0
Ministry of Science and Higher Education. (2022). *National Center for Research and Development: Who we are*. The National Center for Research and Development. https://www.gov.pl/web/ncbr/narodowe-centrum-badan-i-rozwoju-kim-jestesmy-tlumaczenie-migowe-i-audiodeskrypcja
Msakni, M. K., Risan, A., & Schütz, P. (2023). Using machine learning prediction models for quality control: A case study from the automotive industry. *Computational Management Science*, *20*(1), 14. https://doi.org/10.1007/s10287-023-00448-0
Mtotywa, M. M. (2022). Developing a Quality 4.0 Maturity Index for Improved Business Operational Efficiency and Performance. *Quality Innovation Prosperity*, *26*(2), 101–127. https://doi.org/10.12776/qip.v26i2.1718
Murugesan, V. (2022). *What is Quality 4.0? And What It Isn't*. LSN Research. https://blog.lnsresearch.com/what-is-quality-4.0-and-what-it-isnt
National Centre Industry 4.0. (2019). *National Centre for Industry 4.0, principles of the Centre*. https://www.ncp40.cz/files/principy-ncp-4-0-approved-2019.pdf
National Centre Industry 4.0. (2017). *National Centre Industry 4.0*. https://www.ncp40.cz/

Nenadál, J. (2020). The New EFQM Model: What is Really New and Could Be Considered as a Suitable Tool with Respect to Quality 4.0 Concept? *Quality Innovation Prosperity*, *24*(1), 17. https://doi.org/10.12776/qip.v24i1.1415
Nenadál, J., Vykydal, D., Halfarová, P., & Tylečková, E. (2022). Quality 4.0 Maturity Assessment in Light of the Current Situation in the Czech Republic. *Sustainability*, *14*(12), 7519. https://doi.org/10.3390/su14127519
Nosalska, K., Piątek, Z. M., Mazurek, G., & Rządca, R. (2019). Industry 4.0: Coherent definition framework with technological and organizational interdependencies. *Journal of Manufacturing Technology Management*, *31*(5), 837–862. https://doi.org/10.1108/JMTM-08-2018-0238
Pelin Yildiz, E. (2022). Augmented Reality Research and Applications in Education. V D. Cvetković (Ed.), *Augmented Reality and Its Application*. IntechOpen. https://doi.org/10.5772/intechopen.99356
Pereira, A. C., & Romero, F. (2017). A review of the meanings and the implications of the Industry 4.0 concept. *Procedia Manufacturing*, *13*, 1206–1214. https://doi.org/10.1016/j.promfg.2017.09.032
Polish Agency for Enterprise Development. (2018). *Who we are?* PARP. https://www.parp.gov.pl/component/parpabout/?view=parpabout
Polish Agency for Enterprise Development. (2023). *The digital transformation of business is gaining momentum: In a month, another program to support digital innovations will start*. PARP. https://www.parp.gov.pl/component/content/article/83888:cyfrowa-transformacja-biznesu-nabiera-tempa-juz-za-miesiac-startuje-kolejny-program-wsparcia-innowacji-cyfrowych
Propris, L., & Bailey, D. (2020). *Industry 4.0 and Regional Transformations*. Routledge.
PwC. (2019). *Digital Maturity Model*. https://www.pwc.com/my/en/services/digital/digital-operations.html
Qi, Q., & Tao, F. (2018). Digital Twin and Big Data Towards Smart Manufacturing and Industry 4.0: 360 Degree Comparison. *IEEE Access*, *6*, 3585–3593. https://doi.org/10.1109/ACCESS.2018.2793265
Radziwill, N. M. (2018). *Quality 4.0: Let's Get Digital - The many ways the fourth industrial revolution is reshaping the way we think about quality*. https://doi.org/10.48550/ARXIV.1810.07829
Reinhard, G., Vedso, J., & Schrauf, S. (2015). *Industry 4.0: Building the digital enterprise"*. PwC.
Sader, S., Husti, I., & Daroczi, M. (2022). A review of quality 4.0: Definitions, features, technologies, applications, and challenges. *Total Quality Management & Business Excellence*, *33*(9–10), 1164–1182. https://doi.org/10.1080/14783363.2021.1944082
Santos, G., Sá, J. C., Félix, M. J., Barreto, L., Carvalho, F., Doiro, M., Zgodavová, K., & Stefanović, M. (2021). New Needed Quality Management Skills for Quality Managers 4.0. *Sustainability*, *13*(11), 6149. https://doi.org/10.3390/su13116149
Santos, R., & Martinho, J. (2019). An Industry 4.0 maturity model proposal. *Journal of Manufacturing Technology Management*, *31*(5), 1023–1043. https://doi.org/10.1108/JMTM-09-2018-0284
Saucedo-Martínez, J. A., Pérez-Lara, M., Marmolejo-Saucedo, J. A., Salais-Fierro, T. E., & Vasant, P. (2018). Industry 4.0 framework for management and operations: A review. *Journal of Ambient Intelligence and Humanized Computing*, *9*(3), 789–801. https://doi.org/10.1007/s12652-017-0533-1

Shutt, S. (2021). Industry 4.0 and the digital workplace revolution. *Backertilly*. https://www.bakertilly.com/insights/industry-4.0-and-the-digital-workplace-revolution
Schuh, G., Anderl, R., Gausemeier, J., Hompel, M., & Wahlster, W. (2017). *Industrie 4.0 Maturity Index: Managing the Digital Transformation of Companies (acatech STUDY)*.
Schumacher, A., Erol, S., & Sihn, W. (2016). A Maturity Model for Assessing Industry 4.0 Readiness and Maturity of Manufacturing Enterprises. *Procedia CIRP*, *52*, 161–166. https://doi.org/10.1016/j.procir.2016.07.040
Sniderman, B., Mahto, M., & Cotteleer, M. (2016). *Industry 4.0 and manufacturing ecosystems*. Deloitte.
Soldatos, J., Gusmeroli, S., Malo, P., & Di Orio, G. (2022). Internet of Things Applications in Future Manufacturing. V P. Friess & O. Vermesan, *Digitising the Industry Internet of Things Connecting the Physical, Digital and VirtualWorlds* (1st vyd., s. 153–183). River Publishers. https://doi.org/10.1201/9781003337966-5
Sony, M., Antony, J., & Douglas, J. A. (2020). Essential ingredients for the implementation of Quality 4.0: A narrative review of literature and future directions for research. *The TQM Journal*, *32*(4), 779–793. https://doi.org/10.1108/TQM-12-2019-0275
Stock, T., & Seliger, G. (2016). Opportunities of Sustainable Manufacturing in Industry 4.0. *Procedia CIRP*, *40*, 536–541. https://doi.org/10.1016/j.procir.2016.01.129
Sütőová, A., Šooš, Ľ., & Kóča, F. (2020). Learning Needs Determination for Industry 4.0 Maturity Development in Automotive Organisations in Slovakia. *Quality Innovation Prosperity*, *24*(3), 122. https://doi.org/10.12776/qip.v24i3.1521
Tercan, H., & Meisen, T. (2022). Machine learning and deep learning based predictive quality in manufacturing: A systematic review. *Journal of Intelligent Manufacturing*, *33*(7), 1879–1905. https://doi.org/10.1007/s10845-022-01963-8
Tsang, Y. P., Choy, K. L., Wu, C. H., Ho, G. T. S., & Lam, H. Y. (2019). Blockchain-Driven IoT for Food Traceability With an Integrated Consensus Mechanism. *IEEE Access*, *7*, 129000–129017. https://doi.org/10.1109/ACCESS.2019.2940227
Wik Consult & VVA. (2019). *Monitoring Progress in National Initiatives on Digitising Industry: Country Report—Slovakia*.
World Economic Forum. (2018). *The Future of Jobs Report 2018*. https://www.weforum.org/reports/the-future-of-jobs-report-2018/
World Economic Forum. (2020). *These are the top 10 job skills of tomorrow – and how long it takes to learn them*. https://www.weforum.org/agenda/2020/10/top-10-work-skills-of-tomorrow-how-long-it-takes-to-learn-them/
Zhang, Y., & Lei, J. (2017). Prediction of Laser Cutting Roughness in Intelligent Manufacturing Mode Based on ANFIS. *Procedia Engineering*, *174*, 82–89. https://doi.org/10.1016/j.proeng.2017.01.152
Zulqarnain, A., Wasif, M., & Iqbal, S. A. (2022). Developing a Quality 4.0 Implementation Framework and Evaluating the Maturity Levels of Industries in Developing Countries. *Sustainability*, *14*(18), 11298. https://doi.org/10.3390/su141811298

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